An Overview of Fixed Passive Acoustic Observation Methods for Cetaceans

BY DAVID K. MELLINGER, KATHLEEN M. STAFFORD, SUE E. MOORE, ROBERT P. DZIAK, AND HARU MATSUMOTO

Cetaceans are increasingly being included as top trophic-level predators in models of ecosystem dynamics (Baumgartner and Mate, 2003; Tynan, 2004; Redfern et al., 2006). Traditional visual survey methods for cetaceans detect only a fraction of the animals present, both because visual observers can see them only during the very short period when they are at the surface, and because visual surveys can be undertaken only during daylight hours in relatively good weather (Mellinger and Barlow, 2003). Perhaps more importantly, visual survey results can be highly variable, due both to clumping of cetaceans into large groups and to their relatively limited spatial and temporal scales. Surveys are typically performed using a small number of observation points—one or a few vessels—for a few weeks to a few months of the year.

> In recent years, passive acoustic methods have become increasingly widespread for cetacean observation.

Acoustic observation may be active or passive. Active acoustics, in which a sound is transmitted and the returning echo analyzed, is widely used for observation of zooplankton and micronekton (primarily fishes, squids, and shrimp), as well as in fisheries research. Here, we describe passive acoustic observation, which is used more widely for cetacean observation. In this type of observation, the instrument used does not produce any sounds itself; it only captures sounds from the surrounding environment. In recent years, passive acoustic methods have become increasingly widespread for cetacean observation (e.g., Moore et al., 2006). In joint visual-acoustic surveys, acoustic modalities have detected one to ten times as many cetacean groups as visual ones (McDonald and Moore, 2002; Širović et al., 2004; Barlow and Taylor, 2005; Rankin et al., 2007), and acoustic observation has the additional advantages that it can continue at night, in poor weather, and under other conditions in which visual observation cannot.

Another distinction in passive acoustic survey methods is that of fixed versus mobile acoustic sensors. Hydrophones may be towed behind a ship or affixed to an ocean glider or other mobile platform to sample a large area. Alternatively, the hydrophone instruments may be left in place for long time periods. Advantages of the mobile approach include large areal coverage and simplicity in combining acoustic detection with a visual survey, while the principal advantages of the fixed approach are that observation usually spans a longer time period and is frequently less expensive.

In this article, we describe the methodology of fixed passive acoustic observations, including instrumentation, software for detection of vocalizations, statistical methods, and interpretation of results, and then provide an example of the results from a fixed passive acoustic survey of Bransfield Strait, Antarctica, supported by the National Oceanic and Atmospheric Administration's (NOAA's) Office of Ocean Exploration.

METHODS

Fixed passive acoustic surveys require several steps, including survey design, placement and sometimes recovery of recording instruments, extraction of vocalizations of interest from recorded data, statistical analysis of vocalizations, and interpretation of the results.

Instrumentation

Two types of passive acoustic equipment are used widely for capturing sound—cabled hydrophones and autonomous recorders. Cabled hydrophones are typically deployed in permanent or semi-permanent installations. Because of the expense of cabled systems, they are in widespread use mainly by navies or other governmental agencies; examples include the Sound Surveillance System of the US Navy; the hydrophone arrays on US Navy test ranges in the Bahamas, southern California, and Hawaii; and the hydrophones of the Comprehensive Test Ban Treaty Organization. The benefits of these systems for scientific research are that they provide data continuously in near-real time (so that rapid response to unusual events is possible), they have hydrophones in pelagic areas where marine mammal surveys are otherwise rare, and their operation and maintenance is funded by external sources. However, these systems typically have access restrictions because of their military or sensitive nature, so that the data are not easily accessible. Further, the recording bandwidth is often restricted to fairly low frequencies due to the nature of the signals for which they were designed. Cabled systems operated by nongovernmental organizations often consist of one or a few hydrophones placed within several kilometers of shore. Their data are more openly accessible but typically cover only relatively small shelf areas. The advent of cabled ocean observatories (e.g., Barnes et al., 2007; ORION Program Office, 2007) promises to extend the capabilities of such non-military systems to larger offshore areas.

Autonomous recorders consist of a hydrophone and a battery-powered data-recording system. These instruments are moored on the seafloor, sometimes with a cable and flotation to buoy the hydrophone sensor up in the water column (e.g., at the depth of the deep sound channel) for periods of up to two years. Depending on the instrument configuration and deployment duration, sound capture happens either continuously or according to a sampling plan. Autonomous hydrophones are typically deployed in arrays of three to ten instruments to provide areal coverage and to allow for localization of sound sources. A number of laboratories have designed and used such instruments since the mid-1990s (Calupca et al., 2000; Fox et al., 2001; Wiggins, 2003; Lammers et al., in press), and more recently a commercial version has become available (http://www.totalsat.qc.ca/mte/aural_en.htm). These instruments store acoustic data internally, so they must be recovered before data analysis can begin.

In addition to the widely used cabled hydrophones and autonomous recorders, radio-linked hydrophones are occasionally used for marine mammal acoustic surveys. These combine a hydrophone sensor on a mooring (Clark et al., 2007) or on shore-fast ice (Clark et al., 1996) with a radio link to a shore station or ship (e.g., Rankin et al., 2005). As with cabled systems, data are captured continuously in real time.

A final variant consists of using marine mammals themselves as platforms for acoustic sensors. By miniaturizing the sensor and electronics package to fit into an attachable tag, the instrument can record acoustic data from areas where the animal itself is exposed. Such tags have been deployed on larger marine mammals, including elephant seals (*Mirounga angustirostris*; Fletcher et al., 1996; Burgess et al., 1998) and several species of mysticete and odontocete whales (Madsen et al., 2002; Johnson and Tyack, 2003).

A key difference in choice of instrumentation is whether hydrophones are deployed in isolation from one another, in distributed small-area arrays for localization, or in large coherent arrays to allow beamforming. When several single sensors are placed tens to hundreds of kilometers apart, they are usually too far apart to detect an individual animal on multiple instruments, so this configuration may be considered to be multiple isolated instruments. When instruments are placed closely enough that three or more can detect a vocalizing animal, then the animal can be located using time-of-arrival differences; localization of successive vocalizations allows the individual to be tracked as it moves (Clark et al., 1996). When approximately 10 or more hydrophones are deployed in a tightly spaced array, a sound wave from an animal arrives coherently at all of the hydrophones, allowing beamforming techniques to be used (Johnson and

Some species are more amenable to accurate acoustic surveys than others.

DAVID K. MELLINGER (*David.Mellinger@oregonstate.edu*) *is Associate Professor, Senior Research, Cooperative Institute for Marine Resources Studies, Oregon State University, and Pacific Marine Environmental Laboratory (PMEL), National Oceanic and Atmospheric Administration (NOAA), Newport, OR, USA.* KATHLEEN M. STAFFORD *is Research Scientist, Applied Physics Laboratory, University of Washington, Seattle, WA, USA.* SUE E. MOORE *is Principal Oceanographer and Senior Scientist, Alaska Fisheries Science Center, NOAA, Seattle, WA, USA.* ROBERT P. DZIAK *is Associate Professor, Senior Research, Cooperative Institute for Marine Resources Studies, Oregon State University, and PMEL/NOAA, Newport, OR, USA.* HARU MATSUMOTO *is Research Associate, Cooperative Institute for Marine Resources Studies, Oregon State University, and PMEL/NOAA, Newport, OR, USA.*

Dudgeon, 1993; Stafford et al., 1998). Beamforming increases the signal-to-noise ratio (SNR) of sound arriving from certain directions such that an N-element hydrophone array provides an "array gain" of approximately $\sqrt{N}$ in SNR, equivalent to an increase in acoustic detection area of approximately *N*.

Behavioral Considerations

Some species are more amenable to accurate acoustic surveys than others. Species-specific factors influencing fixed passive acoustic surveys include these:

- **Frequency.** Sounds below 1 kHz have significantly less seawater absorption loss than sounds above 10 kHz (François and Garrison, 1982), and thus can be detected at greater distances. The former frequencies are typical of mysticetes, while the latter are typical of odontocetes. Figure 1 shows the frequency ranges of cetacean vocalizations.
- **Vocal behavior.** Some cetaceans vocalize more frequently or more consistently than others, making them better subjects for acoustic surveys. Vocalizing behavior varies with gender, age, and season. For instance, adult males of many baleen whale species vocalize regularly and loudly during the breeding season.
- **Source level.** The larger cetaceans, including mysticete whales and sperm whales, produce intense vocalizations that can be detected at distances of several tens of kilometers on a single hydrophone (Barlow and Taylor, 2005; Stafford et al., in press) and much farther—hundreds of kilometers—on hydrophone arrays (Clark, 1995). For instance, blue whale (*Balaenoptera musculus*) tonal calls have been measured over 185 dB RMS re 1 µPa @ 1 m (Cummings and Thompson, 1971; McDonald et al., 2001; Thode et al., 2000; Širović et al., 2007), while on-axis sperm whale clicks have been measured at instantaneous levels up to 223 dB re 1 µPa peak equivalent RMS @ 1 m (Møhl et al., 2000). In contrast, bottlenose dolphin (*Tursiops truncatus*) tonal sounds (whistles) have been measured at source levels up to 169 dB re 1 µPa RMS @ 1 m (Janik, 2000),

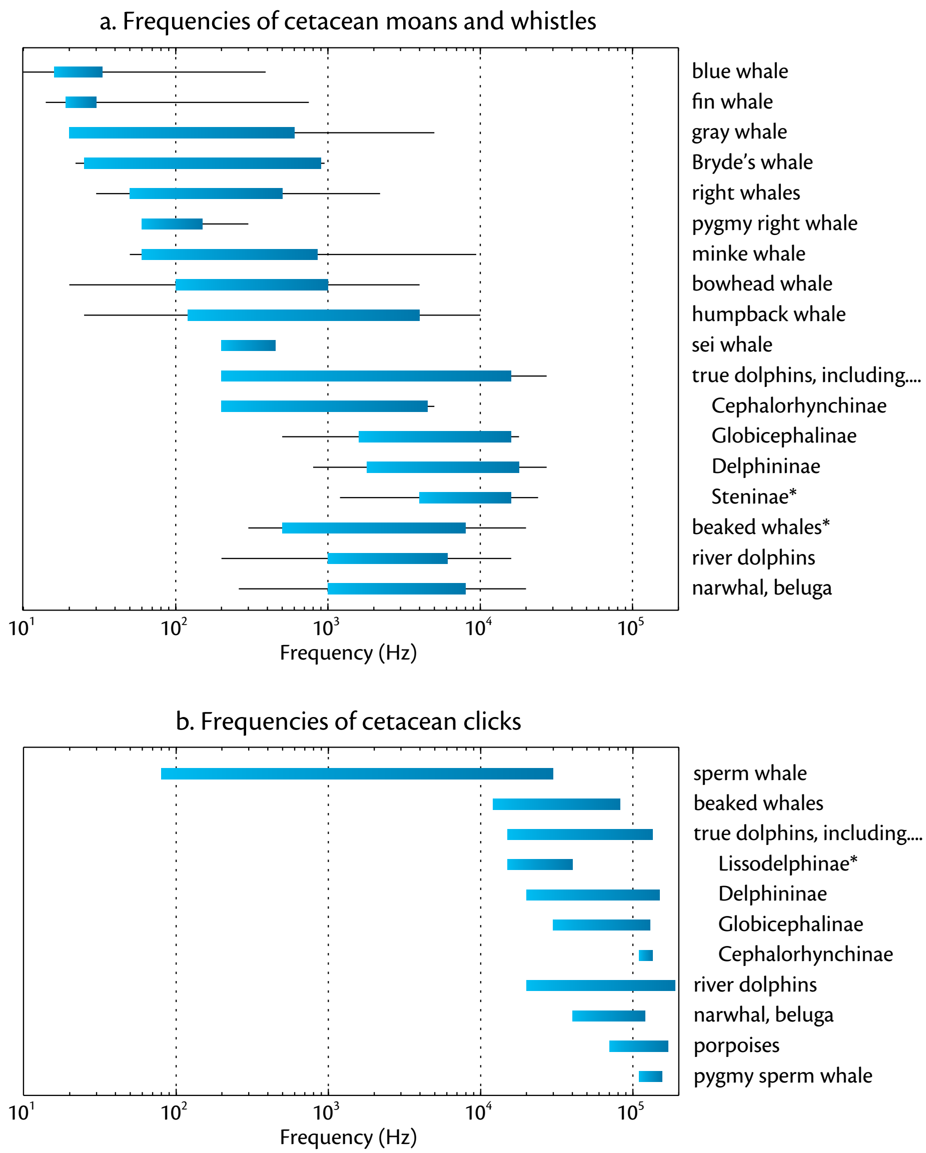

Figure 1. Known frequency ranges of cetacean sounds. Large whales are listed by species, while toothed whales are grouped into families. The thick bar shows the range of the most common types of vocalizations, while the thinner line shows recorded extremes of frequency. An asterisk (*) indicates that the upper frequency is unknown because of recording equipment limitations. (a) Tonal sounds—moans and whistles—with most baleen whale species shown separately. (b) Echolocation clicks. Baleen whales do not produce high-frequency echolocation clicks, while some toothed whales, dolphins, and porpoises do not produce tonal sounds.

while their clicks have been measured at 210–213 dB re 1 μPa RMS @ 1 m (Au et al., 1986).

- Directionality. High-frequency click sounds of some odontocetes are highly directional. For instance, the directionality index for bottlenose dolphins is at least 26 dB (Au, 1993), and sperm whale sound emission is at least 35 dB louder in some directions than others (Møhl et al., 2000). In contrast, low-frequency baleen whale sounds are believed to be emitted essentially omnidirectionally, in part because the long wavelengths make directional sound emission all but impossible.

Detection of Vocalizations

Vocalizations of a target species can be detected manually, with specialists listening to sounds and/or looking at spectrograms to find occurrences of these species' vocalizations (Clark et al., 1996; Stafford et al., 1999, 2001). The volumes of data involved, however, more often dictate using automatic detection.

Many methods for detection and classification have been developed and tested. Most are based on detection either in a time series or in a spectrogram, though other methods like wavelets are used as well. Techniques involved include matched filters (Stafford, 1995), energy summation in a certain band followed by statistical classification (Fristrup and Watkins, 1994; Oswald et al., 2004), image-processing techniques in spectrograms (Gillespie, 2004), spectrogram-based template matching (Mellinger and Clark, 2000), neural networks (Potter et al., 1994), wavelet-based decomposition (Lopatka et al., 2005), band-limited amplitude in either the time series (Gillespie and Chappell, 2002) or spectrogram (Mellinger et al., 2004a), and many more.

Whatever the method used, two issues are paramount. The first is determining the type(s) of vocalizations to be detected and the amount of variability in these vocalizations. Some species, such as populations of fin whales (*B. physalus*), have highly stereotyped vocalizations. These are amenable to detection using one of the template-matching methods mentioned above. Other species, such as common dolphins (*Delphinus delphis*), produce highly variable tonal sounds (Oswald et al., 2004). These typically require band-limited energy summation for detection, possibly followed by statistical classification techniques for species classification. Other species produce sounds with intermediate levels of variability that can be detected using neural networks (Potter et al., 1994) and filter banks (Urazghildiiev and Clark, 2006).

The second issue is the desired accuracy of detection. In a perfect world, a detection method would find all instances of a certain call type, and nothing more. This ideal is never met, in part because there are inevitably faint calls that are difficult to classify, even by the best human specialists. The issue then becomes one of configuring the detector's sensitivity, or threshold, to achieve a certain trade-off between missed calls (false negatives) and wrong detections (false positives). For a survey of a relatively rare species such as right whales (*Eubalaena* spp.), for which one wishes to miss no calls, detection can be configured at a relatively sensitive level so that there are no or few missed calls but a large number of false detections; the resulting detections can be checked manually to determine which really were from the desired species (Mellinger et al., 2004b; Munger et al., 2005). For a survey of a common species such as fin whales, for which determining an accurate index of call occurrence is paramount, detection can be configured to be relatively insensitive, so that there are few wrong detections and a very high proportion of correct detections. For a survey using the cue-counting statistical methods discussed below, it may be important to have the number of missed calls be as equal as possible to the number of false detections, so an intermediate sensitivity is used.

APPLICATIONS AND ANALYTICAL METHODS

Determining Range and Seasonality

Acoustic surveys have been used many times to measure the range and seasonal occurrence of cetaceans. One advantage of fixed passive acoustic methods is that they can be performed year round at relatively low cost (e.g., Thompson and Freidl, 1982). Also, they can be carried out in remote areas that are difficult to survey other ways, such as far from land (Clark, 1995; Stafford et al., 1999; Nieukirk et al., 2004), polar regions (Širović et al., 2004, 2007; Munger et al., 2005; Moore et al., 2006; Stafford et al., 2007; and see "An Example Survey" below), or where weather is poor, and visual surveys impossible, in some seasons (Mellinger et al., 2007).

In such studies, the number of vocalizations in each time period (e.g., each day, each month, each ten-day period) is counted, providing a rough indication of the number of animals in an area (e.g., Širović et al., 2004). Another method is to measure the amount of energy in the frequency band of the vocalization type, correct it for background noise level, and use that as an indication of the number of calls (e.g., Burtenshaw et al., 2004). Unfortunately, the connection between the number of vocalizations and the number of animals is tenuous at best; sometimes a single animal produces a rapid sequence of vocalizations in a short time, sometimes only an occasional sound. To correct for these behavioral differences, many studies have assessed the number of hours (or number of days) that contain at least one vocalization; this method greatly reduces the bias of a rapidly vocalizing individual, because one vocalization in a given time period has as much weight as many in that period. However, this method also effectively ignores multiple individuals vocalizing in the same time period, so it is better suited for surveys of relatively rare species, such as blue or right whales, than relatively common ones, such as fin whales or common dolphins. In any case, these methods provide at best an index of occurrence, and are perhaps best employed to determine when throughout the year a given species is present in an area (see, e.g., Clark, 1995; Mellinger et al., 2004a, 2004b; Munger et al., 2005).

Abundance

Using a set of detected vocalizations to estimate the abundance of a species in a given area may be done in several ways. One is to derive the probability of detection as a function of range. This probability density function (PDF) may then be inverted using point-transect statistical methods (Buckland et al., 2001), which essentially extrapolate from the number of animals detected near the sensor to the number of animals present and vocalizing in some larger area. The PDF can be estimated either by (1) acoustically locating the animals, such as recordings from multiple hydrophones and using time-of-arrival differences to estimate position (Cummings et al., 1964), (2) estimating range to a vocal animal using acoustic multipath propagation effects (Cato, 1998; McDonald and Fox, 1999; McDonald and Moore, 2002; Širović et al., 2007), or (3) using acoustic propagation models and distributions of source levels to estimate range from received levels (Cato, 1991). Point-transect sampling requires behavioral information on rates of animal movement through the monitored area to avoid double counting of individuals.

Nearly all of these methods require acoustic estimation of group size, a field of study still in its infancy. Although many species have different vocal behavior in the presence of different numbers of conspecifics (e.g., Parks et al., 2005), the relationship between vocal behavior and group size is rarely hard and fast, and the consequent errors in abundance estimates can be large.

A second general approach relies on cue-counting statistical techniques. Here the total number of vocalizations—"cues"—is combined with an estimate of the average cue rate per animal per unit time to estimate the number of animals detected (Buckland et al., 2001). This figure is then extrapolated to estimate the number of animals in the study area. This method requires detailed behavioral information on the rate of cue production, and for most species little information is available.

To estimate density or abundance in a given area using fixed instruments, instrument positions should be chosen without any bias toward any part of the area. This can be done by random positioning of individual instruments or by positioning a regular grid of instruments with a randomly chosen origin.

Another approach is to perform joint visual and acoustic surveys, then combine the results statistically to achieve a better estimate than is possible for either method alone (Fristrup and Clark, 1997). Notably, this has been done for migrating bowhead whales, for which the visual observers count silent whales and the acoustic observers determine the proportion of unseen whales (Clark et al., 1996; Raftery and Zeh, 1998). Another example comes from a survey of sperm whale abundance in the east-

...there are still numerous hurdles to be overcome before acoustic methods can be reliably used to estimate abundance, which is the ultimate goal for both ecosystem studies and management purposes.

ern Pacific, for which the visual component of the survey performed best at estimating group size, while the acoustic component performed best at detecting groups (Barlow and Taylor, 2005).

An additional use of acoustic monitoring in joint surveys is acoustic species identification (Oswald et al., 2003). This becomes useful when shipboard surveys target species that are difficult to identify visually at a distance. This method has been used on eastern tropical Pacific dolphin abundance cruises where dolphin pods often show ship avoidance at distances greater than those at which they can be reliably identified using visual cues. The ability to use acoustic characteristics to determine species/species composition may determine whether or not the ship turns towards the target species or continues along its track to search for that species (Oswald et al., 2007).

AN EXAMPLE SURVEY

In November 2005, with support from NOAA's Office of Ocean Exploration, six autonomous hydrophones were deployed in the Bransfield Strait near the Antarctic Peninsula and one in the Drake Passage to monitor seismicity and large whale occurrence around the South Shetland Islands (Figure 2). The bottom-anchored moorings placed the instruments in the sound channel. Six of the seven instruments recorded acoustic data from 0.1–110 Hz and the seventh sampled from 0.1–840 Hz. Although the bandwidth of the first six instruments was sufficient to record blue and fin whale calls, the seventh was set to record other species known to occur in the area, such as humpback (*Megaptera novaeangliae*) and right whales. The instruments were recovered and redeployed in the same area in December 2006.

A cursory review of spectrograms revealed known signature calls of blue, fin, and humpback whales as well as earthquakes and ice noise. To assess the seasonal presence of Antarctic blue whales, data were automatically scanned by use of a spectrogram correlation routine (Mellinger and Clark, 2000) to detect their characteristic 28-Hz calls. In order to minimize false detections, the detection threshold was set sufficiently high that only these calls were detected. Figure 3 shows the seasonal occurrence of blue whales recorded by the Drake Passage hydrophone. This type of analysis provides information on the seasonal and geographic patterns of calling whales but cannot provide reliable estimates of the number of animals present beyond a minimum of animals vocalizing at the same time. Nevertheless, in remote regions, this method can provide useful, novel information on species occurrence that can be achieved with a few, widely spaced instruments.

To better estimate the number of vocal animals of a particular species in a region, the ability to track the animals is required. This method provides estimates of the vocal behavior of individuals as well as an idea of how many other vocal animals are present at the same time (e.g., Širović et al., 2007). To do this requires a minimum of three, and ideally four, instruments spaced closely enough that the same call is recorded on all of them but widely enough that animals may be located within a broad area. The six instruments in the Bransfield Strait region fit these requirements for

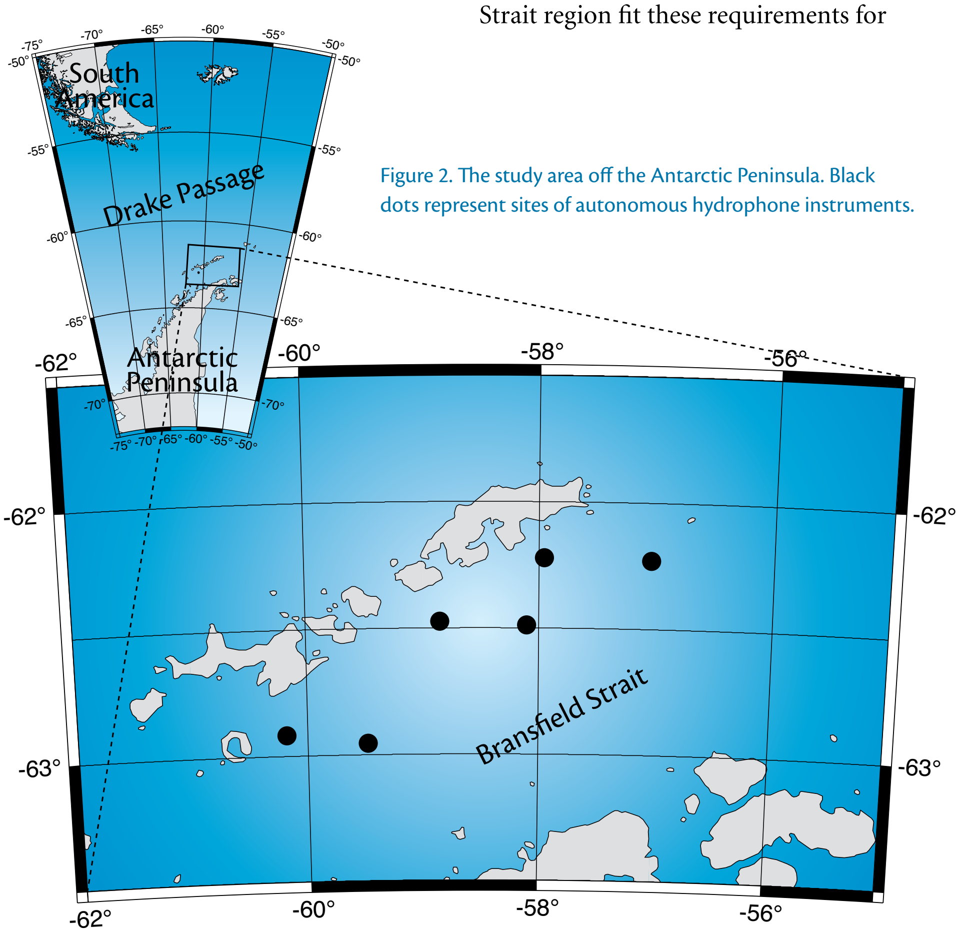

Figure 2. The study area off the Antarctic Peninsula. Black dots represent sites of autonomous hydrophone instruments.

both blue and fin whales. A 15-hour track from a single vocalizing blue whale shows movement from the northeast to the southwest in the array on February 22, 2006 (Figure 4).

These are only two examples of how a long-term multi-instrument data set can be exploited. Other possibilities include comparing acoustic data with ice cover to determine if the latter appears to influence the former. Multiyear acoustic monitoring can provide information on interannual and interseasonal patterns in call reception of all vocal species. These patterns may then be correlated with long-term measurements of physical and lower-trophic parameters to gain a better understanding of the factors affecting, and affected by, cetaceans.

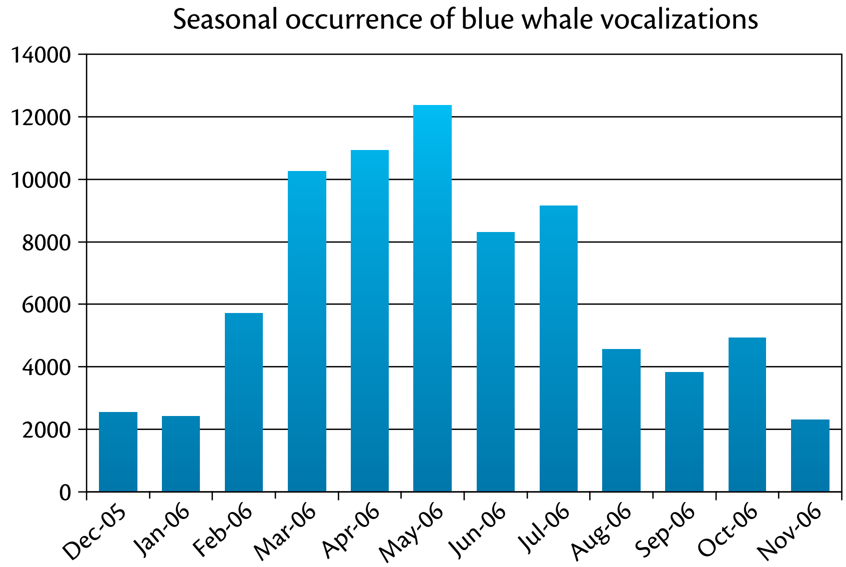

Figure 3. Seasonal occurrence of blue whale vocalizations at the southwestern hydrophone site. Blue whale calls occur in the largest numbers late in the austral autumn (April–May).

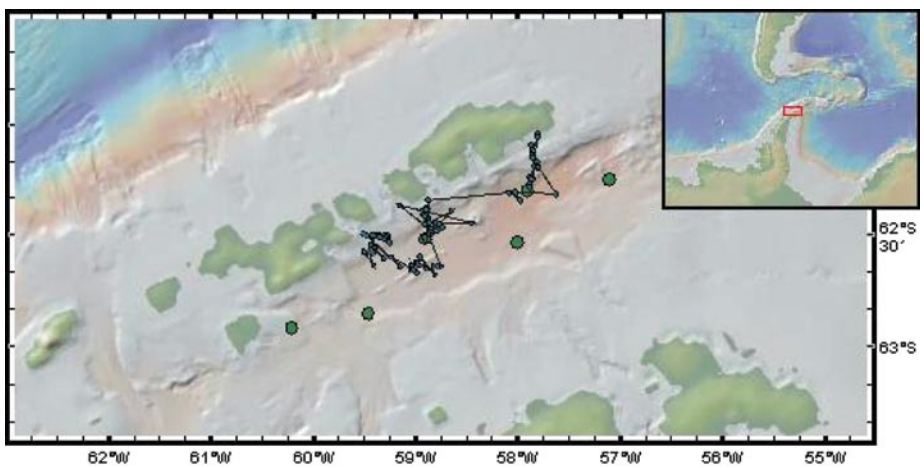

Figure 4. Track of a single blue whale moving through the study area. Whale calls were repeatedly located by time-of-arrival differences at the hydrophones; tracking was possible because it was the only vocalizing blue whale in the area.

DISCUSSION

Passive acoustic methods have been increasingly employed both as standalone surveys and in conjunction with visual surveys. Their utility has become clear over the past decade, and many cetacean surveys now include some acoustic component. However, despite the proliferation of such surveys, there are still numerous hurdles to be overcome before acoustic methods can be reliably used to estimate abundance, which is the ultimate goal for both ecosystem studies and management purposes. Perhaps the biggest hurdle is a general lack of understanding of the behavioral context of sound production for many species, compounded by interspecies differences in acoustic behavior. For instance, odontocetes tend to be highly vocal compared to baleen whales; however, because their vocalizations are higher in frequency than those of most baleen whales, they are detected at shorter distances. Therefore, assessment modalities may need to be tailored for individual species or suites of species. One way to alleviate this problem is to develop statistical models similar to those employed for visual surveys to account for variability in sound production and reception distance. Required information includes distribution curves for seasonal, sex, and age-class bias in sound production, frequency range of species-specific sound characteristics, and source sound level variation.

There is a need to standardize methods among different projects. For example, recordings of blue whales around the Antarctic have been made from near-bottom hydrophones (Širović et al., 2004, 2007), near-surface sonobuoys (Rankin et al., 2005), and autonomous hydrophones moored in the deep sound channel (discussed in this article). A comparison of data from these projects would require standardizing among them, a procedure that would necessarily rely on understanding the acoustic propagation environment in which the sounds travel from source to receiver.

The Acoustical Society of America has recently convened a working group to develop standards for hardware and software for marine mammal monitoring during seismic surveys. At present, only recommendations have been made, but these include the need to define necessary metadata and data needed while at sea, the metrics needed to quantify raw acoustic data, and information that should be reported in the open literature (Aaron Thode, Scripps Institution of Oceanography, *pers. comm.*, December 2006).

The use of passive acoustics worldwide, coupled with effective standardization and development of statistical methods for estimating populations acoustically, should result in more and better data on cetacean species and populations and should ultimately lead to increased understanding of their role in marine ecosystems.

ACKNOWLEDGEMENTS

Thanks to Joe Haxel, Matt Fowler, and Sara Heimlich for assistance configuring, deploying, and recovering the hydrophone instruments used in this project. Thanks also to Minkyu Park and the Korea Polar Research Institute (KOPRI) for ship time in Antarctica. The manuscript was improved thanks to critical reviews by Jay Barlow and Sofie Van Parijs. This work was supported by NOAA's Office of Ocean Exploration and by Naval Postgraduate School award #N00244-07-1-0005. This is PMEL contribution #3116.

REFERENCES

Au, W.W.L. 1993. *The Sonar of Dolphins*. Springer-Verlag, New York, 277 pp.

Au, W.W.L., P.W.B. Moore, and D. Pawloski. 1986. Echolocation transmitting beam of the Atlantic bottlenose dolphin. *Journal of the Acoustical Society of America* 80:688–691.

Barlow, J., and B.L. Taylor. 2005. Estimates of sperm whale abundance in the northeastern temperate Pacific from a combined acoustic and visual survey. *Marine Mammal Science* 21:429–445.

Barnes, C.R., M.M.R. Best, B.D. Bornhold, S.K. Juniper, B. Pirenne, and P. Phibbs. 2007. The NEPTUNE Project—a cabled ocean observatory in the NE Pacific: Overview, challenges and scientific objectives for the installation and operation of Stage I in Canadian waters. Pp. 308–313 in *Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies*, Tokyo, Japan. IEEE Press, Piscataway, NJ, doi:10.1109/UT.2007.370809.

Baumgartner, M.F., and B.R. Mate. 2003. Summertime foraging ecology of North Atlantic right whales. *Marine Ecology Progress Series* 264:123–135.

Buckland, S.T., D.R. Anderson, K.P. Burnham, J.L. Laake, D.L. Borchers, and L. Thomas. 2001. *Introduction to Distance Sampling: Estimating Abundance of Biological Populations* (Oxford University, Oxford), 448 pp.

Burgess, W.C., P.L. Tyack, B.J. Le Boeuf, and D.P. Costa. 1998. A programmable acoustic recording tag and first results from northern elephant seals. *Deep-Sea Research Part II* 45:1,327–1,351.

Burtenshaw, J.C., E.M. Oleson, J.A. Hildebrand, M.A. McDonald, R.K. Andrew, B.M. Howe, and J.A. Mercer. 2004. Acoustic and satellite remote sensing of blue whale seasonality and habitat in the northeast Pacific. *Deep Sea Research Part II* 51:967–986.

Calupca, T.A., K.M. Fristrup, and C.W. Clark. 2000. A compact digital recording system for autonomous bioacoustic monitoring. *Journal of the Acoustical Society of America* 108:2582(A).

Cato, D. 1991. Songs of humpback whales: The Australian perspective. *Memoirs of the Queensland Museum* 30:277–290.

Cato, D.H. 1998. Simple methods of estimating source levels and locations of marine animal sounds. *Journal of the Acoustical Society of America* 104:1,667–1,678.

Clark, C.W. 1995. Application of U.S. Navy underwater hydrophone arrays for scientific research on whales. *Scientific Report, International Whaling Commission* 44:210–213.

Clark, C.W., R.A. Charif, S.G. Mitchell, and J. Colby. 1996. Distribution and behavior of the bowhead whale, *Balaena mysticetus*, based on analysis of acoustic data collected during the 1993 spring migration off Point Barrow, Alaska. *Scientific Report, International Whaling Commission* 46:541–552.

Clark, C.W., D. Gillespie, D.P. Nowacek, and S.E. Parks. 2007. Listening to their world: Acoustics for monitoring and protecting right whales in an urbanized world. Pp. 333–357 in *The Urban Whale*, S.D. Kraus and R.M. Rolland, eds, Harvard University Press, Cambridge, MA.

Cummings, W.C., and P.O. Thompson. 1971. Underwater sounds from the blue whale, *Balaenoptera musculus*. *Journal of the Acoustical Society of America* 50:1,193–1,198.

Cummings, W.C., B.D. Brahy, and W.F. Herrnkind. 1964. The occurrence of underwater sounds of biological origin off the west coast of Bimini, Bahamas. Pp. 27–43 in *Marine Bio-acoustics*, W.N. Tavolga, ed., Pergamon, NY.

Fletcher, S., B.J. Le Boeuf, D.P. Costa, P.L. Tyack, and S.B. Blackwell. 1996. Onboard acoustic recording from diving northern elephant seals. *Journal of the Acoustical Society of America* 100:2,531–2,539.

Fox, C.G., H. Matsumoto, and T.K.A. Lau. 2001. Monitoring Pacific Ocean seismicity from an autonomous hydrophone array. *Journal of Geophysical Research* 106(B3):4,183–4,206.

François, R.E., and G.R. Garrison. 1982. Sound absorption based on ocean measurements: Part II: Boric acid contribution and equation for total absorption. *Journal of the Acoustical Society of America* 72:1,879–1,890.

Fristrup, K.M., and C.W. Clark. 1997. Combining visual and acoustic survey data to enhance density estimation. *Scientific Report, International Whaling Commission* 47:933–936.

Fristrup, K.M., and W.A. Watkins. 1994. Marine animal sound classification. *Technical Report WHOI-94-13*, Woods Hole Oceanographic Institution, Woods Hole, MA. 32 pp.

Gillespie, D. 2004. Detection and classification of right whale calls using an edge detector operating on a smoothed spectrogram. *Canadian Acoustics* 32:39–47.

Gillespie, D., and O. Chappell. 2002. An automatic system for detecting and classifying the vocalisations of harbour porpoises. *Bioacoustics* 13:37–61.

Janik, V.M. 2000. Source levels and the estimated active space of bottlenose dolphin (*Tursiops truncatus*) whistles in the Moray Firth, Scotland. *Journal of Comparative Physiology A* 186:673–680.

Johnson, D.H., and D.E. Dudgeon. 1993. *Array Signal Processing: Concepts and Techniques*. Prentice-Hall, Englewood Cliffs, NJ, 533 pp.

Johnson, M.P., and P.L. Tyack. 2003. A digital acoustic recording tag for measuring the response of wild marine mammals to sound. *IEEE Journal of Oceanic Engineering* 28:3–12.

Lammers, M.O., R.E. Brainard, W.W.L. Au, T.A. Mooney, and K. Wong. In press. Ecological Acoustic Recorder (EAR) for long-term monitoring of biological and anthropogenic sounds on coral reefs and other marine habitats. *Journal of the Acoustical Society of America*.

Lopatka, M., O. Adam, C. Laplanche, J. Zarzycki, and J.-F. Motsch. 2005. An attractive alternative for sperm whale click detection using the wavelet transform in comparison to the Fourier spectrogram. *Aquatic Mammals* 31:463–467.

Madsen, P.T., R. Payne, N.U. Kristiansen, M. Wahlberg, I. Kerr, and B. Møhl. 2002. Sperm whale sound production studied with ultrasound time/depth recording tags. *Journal of Experimental Biology* 205:1,899–1,906.

McDonald, M.A., and C.G. Fox. 1999. Passive acoustic methods applied to fin whale population density estimation. *Journal of the Acoustical Society of America* 105:2,643–2,651.

McDonald, M.A., and S.E. Moore. 2002. Calls recorded from North Pacific right whales (*Eubalaena japonica*) in the eastern Bering Sea. *Journal of Cetacean Research and Management* 4:261–266.

McDonald, M.A., J. Calambokidis, A.M. Teranishi, and J.A. Hildebrand. 2001. The acoustic calls of blue whales off California with gender data. *Journal of the Acoustical Society of America* 109:1,728–1,735.

Mellinger, D.K., and J. Barlow. 2003. Future directions for marine mammal acoustic surveys: Stock assessment and habitat use. Report of a workshop held in La Jolla, CA, November 20–22, 2002. Technical contribution No. 2557, NOAA Pacific Marine Environmental Laboratory, Seattle, WA, 45 pp.

Mellinger, D.K., and C.W. Clark. 2000. Recognizing transient low-frequency whale sounds by spectrogram correlation. *Journal of the Acoustical Society of America* 107:3,518–3,529.

Mellinger, D.K., K.M. Stafford, and C.G. Fox. 2004a. Seasonal occurrence of sperm whale (*Physeter macrocephalus*) sounds in the Gulf of Alaska, 1999–2001. *Marine Mammal Science* 20:48–62.

Mellinger, D.K., K.M. Stafford, S.E. Moore, L. Munger, and C.G. Fox. 2004b. Detection of North Pacific right whale (*Eubalaena japonica*) calls in the Gulf of Alaska. *Marine Mammal Science* 20:872–879.

Mellinger, D.K., S.L. Nieukirk, H. Matsumoto, S.L. Heimlich, R.P. Dziak, J. Haxel, M. Fowler, C. Meinig, and H.V. Miller. 2007. Seasonal occurrence of North Atlantic right whales (*Eubalaena glacialis*) at two sites on the Scotian Shelf. *Marine Mammal Science* 23:856–867.

Møhl, B., M. Wahlberg, P.T. Madsen, L.A. Miller, and A. Surlykke. 2000. Sperm whale clicks: Directionality and source level revisited. *Journal of the Acoustical Society of America* 107:638–648.

Moore, S.E., K.M. Stafford, D.K. Mellinger, and J.A. Hildebrand. 2006. Listening for large whales in offshore waters of Alaska. *BioScience* 56:49–55.

Munger, L.M., D.K. Mellinger, S.M. Wiggins, S.E. Moore, and J.A. Hildebrand. 2005. Performance of spectrogram correlation in detecting right whale calls in long-term recordings from the Bering Sea. *Canadian Acoustics* 33:25–34.

Nieukirk, S.L., K.M. Stafford, D.K. Mellinger, R.P. Dziak, and C.G. Fox. 2004. Low-frequency whale and airgun sounds recorded from the mid-Atlantic Ocean. *Journal of the Acoustical Society of America* 115:1,832–1,843.

ORION Program Office. 2007. ORION's ocean observatories initiative conceptual network design. Technical report, Joint Oceanographic Institutions, Washington, D.C. 35 pp.

Oswald, J.N., J. Barlow, and T. Norris. 2003. Acoustic identification of nine delphinid species in the eastern tropical Pacific Ocean. *Marine Mammal Science* 19:20–37.

Oswald, J.N., S. Rankin, and J. Barlow. 2004. The effect of recording and analysis bandwidth on acoustic identification of delphinid species. *Journal of the Acoustical Society of America* 116:3,178–3,185.

Oswald, J.N., S. Rankin, J. Barlow, and M.O. Lammers. 2007. A tool for real-time acoustic species identification of delphinid whistles. *Journal of the Acoustical Society of America* 122:587–595.

Parks, S.E., and P.L. Tyack. 2005. Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups. *Journal of the Acoustical Society of America* 117:3,297–3,306.

Potter, J.R., D.K. Mellinger, and C.W. Clark. 1994. Marine mammal call discrimination using artificial neural networks. *Journal of the Acoustical Society of America* 96:1,255–1,262.

Raftery, A.E., and J.E. Zeh. 1998. Estimating bowhead whale population size and rate of increase from the 1993 census. *Journal of the American Statistical Association* 93:451–463.

Rankin, S., D.K. Ljungblad, C.W. Clark, and H. Kato. 2005. Vocalizations of Antarctic blue whales, Balaenoptera musculus intermedia, recorded during the 2001–2002 and 2002–2003 IWC-SOWER circumpolar cruises, Area V, Antarctica. Journal of Cetacean Research and Management 7:13–20.

Rankin, S., T.F. Norris, M.A. Smultea, C. Oedekoven, A.M. Zoidis, E. Silva, and J. Rivers. 2007. A visual sighting and acoustic detections of minke whales, *Balaenoptera acutorostrata* (Cetacea: Balaenopteridae), in nearshore Hawaiian waters. *Pacific Science* 61:395–398.

Redfern, J.V., M.C. Ferguson, E.A. Becker, K.D. Hyrenbach, C. Good, J. Barlow, K. Kaschner, M.F. Baumgartner, K.A. Forney, L.T. Ballance, and others. 2006. Techniques for cetacean-habitat modeling. *Marine Ecology Progress Series* 310:271–295.

Širović, A., J.A. Hildebrand, S.M. Wiggins, M.A. McDonald, S.E. Moore, and D. Thiele. 2004. Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula. *Deep-Sea Research Part II* 51:2,327–2,344.

Širović, A., J.A. Hildebrand, and S.M. Wiggins. 2007. Blue and fin whale call source levels and propagation range in the Southern Ocean. *Journal of the Acoustical Society of America* 122:1,208–1,215.

Stafford, K.M. 1995. Characterization of blue whale calls from the northeast Pacific and development of a matched filter to locate blue whales on U.S. Navy SOSUS (SOund SUrveillance System) arrays. Master's Thesis, Oregon State University, Corvallis, OR.

Stafford, K.M., C.G. Fox, and D.S. Clark. 1998. Long-range detection and localization of blue whale calls in the northeast Pacific using military hydrophone arrays. *Journal of the Acoustical Society of America* 104:3,616–3,625.

Stafford, K.M., S.L. Nieukirk, and C.G. Fox. 1999. Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific. *Journal of the Acoustical Society of America* 106:3,687–3,698.

Stafford, K.M., S.L. Nieukirk, and C.G. Fox. 2001. Geographic and seasonal variation of blue whale calls in the North Pacific. *Journal of Cetacean Research and Management* 3:65–76.

Stafford, K.M., S.E. Moore, M. Spillane, and S. Wiggins. 2007. Gray whale calls recorded near Barrow, Alaska, throughout the winter of 2003–04. *Arctic* 60:167–172.

Stafford, K.M., D.K. Mellinger, S.E. Moore, and C.G. Fox. In press. Seasonal variability and detection range modeling of baleen whale calls in the Gulf of Alaska, 1999–2002. *Journal of the Acoustical Society of America*.

Thode, A.M., G.L. D'Spain, and W.A. Kuperman. 2000. Matched-field processing, geoacoustic inversion, and source signature recovery of blue whale vocalizations. *Journal of the Acoustical Society of America* 107:1,286–13,00.

Thompson, P.O., and W.A. Friedl. 1982. A long-term study of low frequency sounds from several species of whales off Oahu, Hawaii. *Cetology* 45:1–19.

Tynan, C.T. 2004. Cetacean populations on the SE Bering Sea shelf during the late 1990s: Implications for decadal changes in ecosystem structure and carbon flow. *Marine Ecology Progress Series* 272:281–300.

Urazghildiiev, I.R., and C.W. Clark. 2006. Acoustic detection of North Atlantic right whale contact calls using the generalized likelihood ratio test. *Journal of the Acoustical Society of America* 120:1,956-1,963.

Wiggins, S.M. 2003. Autonomous acoustic recording packages (ARPs) for long-term monitoring of whale sounds. *Marine Technology Society Journal* 37(2):13–22.